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Assessing the impact of climate change on water resources of upper Awash River sub-basin, Ethiopia

Eshetu Ararso Heyi[1)], Megersa Olumana Dinka[2)] ✉ iD, Girma Mamo[3)] iD

[1)] Oromia Agricultural Research Institute, Agricultural Engineering Research Directorate, Addis Ababa, Ethiopia

[2)] University of Johannesburg, Faculty of Engineering and the Built Environment, Department of Civil Engineering Sciences, PO Box 524, Auckland Park, 2006 Johannesburg, South Africa

[3)] Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia

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Abstract: This study tried to assess the impact of climate change on water resources of the upper Awash River sub-basin (Ethiopia) using a statistical downscaling model (SDSM). The future climatic parameters (rainfall, maximum and minimum temperatures) were generated by downscaling outputs of HadCM3 (Hadley Centre Coupled Model, version 3) general circulation model to watershed level for A2a (medium-high) and B2a (medium-low) emission scenarios at representative stations (Addis Ababa, Ginchi and Bishoftu). These SDSM generated climatic data were used to develop current/baseline period (1971–2010) and future climate change scenarios: 2020s (2011–2040), 2050s (2041–2070) and 2080s (2071–2099). The projected future rainfall and mean monthly potential evapotranspiration at these stations were weighted and fed to HBV hydrological model (Hydrologiska Byråns Vattenbalansavdelning model) for future stream flow simulation. These simulated future daily flow time series were processed to monthly, seasonal and annual time scales and the values were compared with that of base period for impact assessment. The simulation result revealed the possibility for significant mean flow reductions in the future during Summer or "Kiremt" (main rainy season) and apparent increase during "Belg" or winter (dry season). Autumn flow volume showed decreasing trend (2020s), but demonstrated increasing trend at 2050s and 2080s. A mean annual flow reduction (ranging from 13.0 to 29.4%) is also expected in the future for the three studied benchmark periods under both emission scenarios. Generally, the result signals that the water resources of upper Awash River basin will be expected to be severely affected by the changing climate. Therefore, different adaptation options should be carried out in order to reduce the likely impact and ensure water security in the sub-basin.

Keywords: climate change, downscaling, emission scenario, hydrologic modelling

INTRODUCTION

Climate change is influencing the spatial and temporal distribution of water resources on global scale [ARNELL 2003; 2004; ARNELL, GOSLING 2013; BATES *et al.* 2008; KUNDZEWICZ *et al.* 2007; OLMSTEAD 2013]. Changes over the last century in seasonal variation in stream flow patterns are increasingly apparent [BATES *et al.* 2008]. Future changes in overall flow magnitude, variability and timing of the main flow events are among the most frequently cited hydrologic issues [ALCAMO *et al.* 2007; SCHNEIDER *et al.* 2013; ZERAY 2006]. These changes have a great impact on hydrologic cycle, quantity and quality of both surface and subsurface water potentials. The changes on temperature and precipitation components of the cycle have direct consequence on evapotranspiration and thus on the runoff components [NKHONGERA, DINKA 2017]. Hence, the spatial and temporal water resources availability and its quality is significantly affected [HAILEMARIAM 1999; NKHONGERA, DINKA 2017]. Climate change on water regime has multiplier effect on other environmental and social factors of water management. For instance, reduced river runoff can concentrate the effects of pollutants or aggravate the spread of water-borne diseases. Climate fluctuations can also affect the use of agricultural land associated with irrigation systems. It also greatly complicates the design, operation and management of water-use systems [Bates *et al.* 2008; Hailemariam 1999].

In Ethiopia, climate variability is already imposing a significant challenge by affecting agricultural production, water and energy supply, thereby deepening poverty reduction and sustainable development endeavours, as well as by causing natural resources degradation and disasters [NMA 2007]. For instance, the impacts of past droughts of the 1973/1974, 1983/1984 and 2002/2003 are still fresh in the memories of many Ethiopians [Chemeda *et al.* 2010]. Floods that occurred in 2006 caused substantial loss of lives and livelihood assets in several parts of the country. These challenges are likely to be exacerbated by climate change [NMA 2007]. Empirical studies also revealed that climate change will affect agricultural production in the country and may lead to 30–46% decline in real GDP in the next 50 years [Gebreegziabher *et al.* 2011; World Bank 2008].

The Awash River is the most utilised river basin in Ethiopia [Dinka 2010; 2012]. It is widely abstracted for renewable energy generation (hydropower), irrigation, domestic and industrial water uses. Irrigation, being the major consumer of water, is the most developed activity in Awash River Basin and has the largest share of sectorial contribution to the Ethiopian economy (i.e. about 3.7% of GDP) [Hagos *et al.* 2009]. There are a number of irrigation schemes ranging from small traditional to large modern scales. Of the total 290,000 ha of irrigated land in the country by 2009, 29% (about 84,100 ha) is in the Awash River Basin involving both traditional and modern small to large-scale irrigation schemes [World Bank 2009]. In addition, new irrigation infrastructures were developed and expansion works of the existing irrigation systems are underway with a few of them under-construction. Moreover, growth of the industrial sector in the country is also putting pressure on the water resources of the basin since majority of the manufacturing plants are set in the basin.

Like any other river basins in Ethiopia, Awash River Basin and its major tributaries have been subjected to major environmental stress. The demand for natural resources by the high and fast growing population is the major challenge for effective agricultural and forestland management. The high pressure on forest, land and soil resources in particular, has led to the exploitation of fragile watersheds and ecosystems that have resulted in loss of vegetation and subsequent soil erosion in the basin [Hailemariam 1999]. Long history of irrigation development in the upper, middle, and lower valleys of the basin resulted in land cover changes (i.e., from grazing and shrub land to agricultural land) and salinity and rising water table problems [Alamirew 2002; Dinka 2012; 2017; Dinka *et al.* 2014]. Furthermore, climate change is likely to be another threat that would affect the water resources availability of the basin in the past as well as in the future. This can be best witnessed by recurrent drought, occurrence of occasional floods [NMA 2007] and projected future likely reduction of flow [Daba *et al.* 2016; Hailemariam 1999].

Limited information is available about the impact of climate change on the water resources of Awash River basin after downscaling coarse General Circulation Models (GCMs) outputs to finer spatial scales which are needed for local impact assessment [Harpham, Wilby 2005; Wilby *et al.* 2004]. Overviews of downscaling approaches have been provided by different authors [Hewitson, Crane 1996; von Storch *et al.* 1993; Wilby, Wigley 1997]. The only available study for the Awash River basin, as far as our knowledge is concerned, is that of Hailemariam [1999], and Daba *et al.* [2016]. Hailemariam [1999] assessed the impact of climate change on water resources of Awash River basin using output from course GCMs that have high uncertainty when used for impact assessment at smaller scale. Little has been done to assess impact of climate change at smaller spatial scale using regional climate models. The aim of this study was, therefore, to assess the likely impacts of climate change on water resources of upper Awash River sub-basin using statistical downscaling techniques. The study tried different downscaling approach that employed several representative stations in contrast to those works [Hailemariam 1999; Zeray 2006] who have utilised single station or single areal values for downscaling purpose.

This study presents the application of the HBV (Hydrologiska Byråns Vattenbalansavdelning) statistical downscaling approach in the Awash River basin. The HBV approach which was originally developed at Swedish Meteorological and Hydrological Institute (SMHI) [Bergström 1976; 1992] for hydropower operation and hydrological forecasting has been found proved to be flexible and robust in solving water resource problems and applications. Its use for operational or scientific applications such as for land use and climate change impact assessments have been reported from more than 50 countries around the world [IHMS 2006]. Bergström *et al.* [2001], for instance, used HBV hydrologic model to assess climate change impact on water resources in Sweden using dynamically downscaled climate scenarios. Other authors [Menzel, Burger 2002; Renner *et al.* 2009; Steele-Dunne *et al.* 2008] have also used this model for climate and land use change impact assessment in different part of the world. There are also several applications of HBV model in Ethiopia for impact assessment of land use and climate change on hydrological water regimes [Belay 2011; Getahun, van Lanen 2015; Mulugeta 2009] since it is robust and less data demanding compared to other physically based models. Mulugeta [2009] conducted study of climate change impact on Gilgel Abay reservoir using HBV and found good model performance (Nash and Suticliffe efficiency greater than 0.80). Similarly, better HBV model efficiency in the range of 0.54–0.81 was also obtained [Belay 2011] during calibration and validation of the model on his study of climate change impact for selected catchments of Nile River Basin using climate scenarios downscaled statistically from regional climate models. Furthermore, Getahun and van Lanen [2015] used this conceptual hydrological model to assess the impacts of land use-cover change on hydrology of Melka Kuntrie sub-basin of upper Awash River Basin and found good model performance.

MATERIALS AND METHODS

BRIEF DESCRIPTION OF THE STUDY AREA

The Upper Awash River Basin is located in the Central Ethiopia, Oromia National Regional State, in the western margin of the Main Ethiopian Rift (MER) (Fig. 1). It is confined within the limits of 37°57′–39°13′ E longitude and 8°9′–9°18′ N latitude with total area of 11,753.6 km^2. Its altitude ranges from 1554 to 3572 m a.s.l. The Awash River flows in NW–SE general direction.

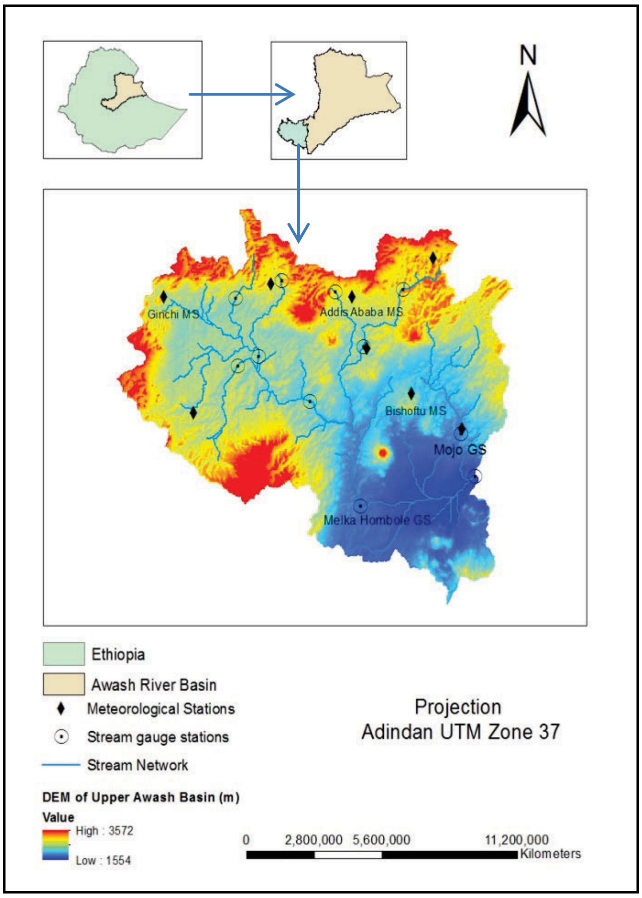


Fig. 1. Location and drainage network map of upper Awash River Basin; source: own elaboration using GIS

Ginchi, Berga, Holeta, Teji, Bantu, Lemen, Akaki and Mojo are the major tributaries of the Awash River in upper part of the basin (Fig. 1). There are artificial and crater lakes in upper Awash. Out of these, Dire, Gefersa and Legedadi were constructed for Addis Ababa city water supply while Abasamuel and Koka were constructed for hydropower generation. The crater lakes are concentrated in the southern part of the study area around Bishoftu town.

The major soil types of the study area include Pellic Vertisols (45.8%), Eutric Nitisols (6.2%), Chromic Luvisols (6.1%), Vertic Cambisols (12.7%) and Luvic Phaeozems (7.3%) (Tab. 1). About 83% areal coverage of the basin is used for agricultural production and it is practiced mostly in both gentle sloping and flat areas (Tab. 2). Cereals like teff, wheat, barley and maize are the major crops grown. Beans, chickpea, guava and oil seeds are also grown but cover less area as compared to cereals. The second most important land use in the area is forest/shrub land. Most of the mountains in the area are covered by forest.

The sub-basin receives large volume of rainfall from June to September, during which over 70% of the annual rain falls, followed by a relatively dry season until the end of January and the small rainy season from February to the end of May (Fig. 2). The average annual rainfall in the basin is about 1200 mm in the highlands and around 1050 mm in the escarpments and below 900 mm in the rift valley part of the study area and the average annual temperature varies from 14.2 to 20.2°C (Tab. 3) with relative cold climate during November and December and warm climate during May (Fig. 2). The average monthly total flow distributions of some gauge stations conform well to the average monthly rainfall (Fig. 3). The flows exhibit similar trends as that of rainfall; the highest flows corresponding the wettest months of July, August and September. The total estimated average annual flow of the sub-basin is about 1904.56 mln m^3 (Tab. 4).

Table 1. Areal coverage of major soil types of upper Awash River sub-basin

Soil type	Area (km^2)	% share
Calcic Xerosols	190.49	1.65
Chromic Cambisols	34.96	0.30
Chromic Luvisols	706.48	6.11
Chromic Vertisols	420.59	3.64
Dystric Nitisols	56.30	0.49
Eutric Cambisols	197.40	1.71
Eutric Fluvisols	295.47	2.56
Eutric Nitisols	721.68	6.24
Leptosols	128.96	1.12
Luvic Phaeozems	845.74	7.31
Orthic Luvisols	8.23	0.07
Orthic Solonchaks	456.83	3.95
Pellic Vertisols	5295.83	45.80
Vertic Cambisols	1466.67	12.68
Vitric Andosols	14.78	0.13
Calcic Fluvisols	70.96	0.61
Mollic Andosols	264.27	2.29
Others	387.998	3.36

Source: own elaboration based on spatial data of MoWR [2006].

Table 2. Areal coverage of different land uses of upper Awash River sub-basin

Land use / land cover	Areal coverage (km^2)	% share
Afro-alpine	0.44	0.00
Cultivation	9796.17	83.34
Grassland	686.12	5.84
Natural forest	131.02	1.11
Plantation	69.71	0.59
Shrub land	539.56	4.59
Urban	143.84	1.22
Water	182.12	1.55
Wetland	180.66	1.54
Woodland	25.40	0.22

Source: own elaboration based on spatial data of MoWR [2006].

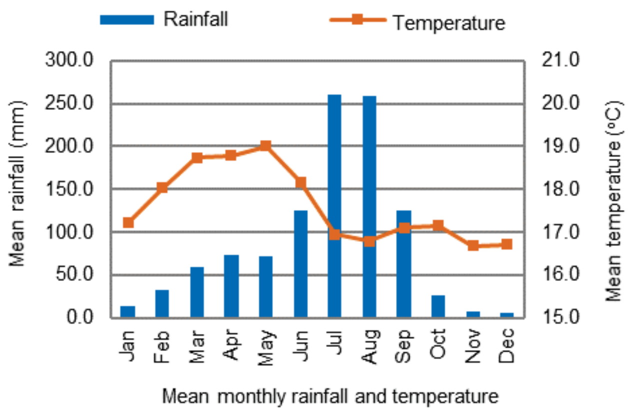


Fig. 2. Mean monthly rainfall and temperature distribution of eight selected stations (1971–2010); source: own elaboration based of data NMA [2007]

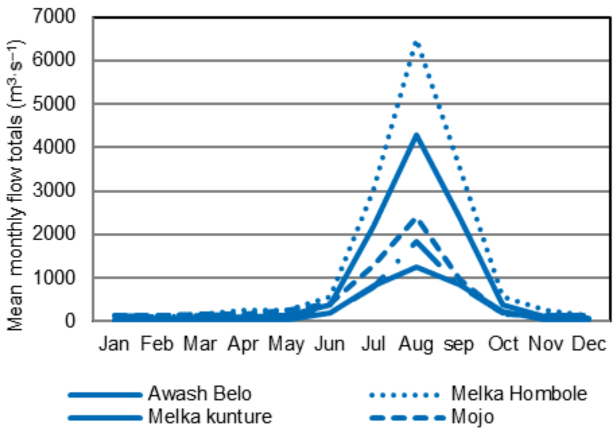


Fig. 3. Mean monthly flow totals of some selected gauge stations within Awash River basin (1971–2008); source: own elaboration based on data of MoWR [2006]

Table 3. Summary of climatic data for selected station and average annual flow at different gauging points for major tributaries and along main river

Station	Period	Latitude (°)	Longitude (°)	Elevation (m a.s.l.)	Mean annual rainfall (mm)	Mean annual temperature (°C)	Relative humidity (%)	Sunshine hours (h)	Wind speed ($m \cdot s^{-1}$)	*ETo* ($mm \cdot day^{-1}$)
Addis Ababa	1971–1995 1981–2000[1)]	9.03	38.75	2354	1032.84	15.9	64.1	7.3	0.6	3.50
Akaki	1971–1995 1996–2009[2)]	8.87	38.80	2120	1173.56	18.5	–	–	–	–
Holota	1971–2000 1981–2000[1)]	9.07	38.48	2380	1063.83	14.2	60.2	6.6	1.2	3.55
Tulubolo	1971–1995 1987–1995[2)]	8.67	38.22	2100	1132.16	15.1	–	–	–	–
Ginchi	1971–2000 1981–2000[1)]	9.03	38.12	2290	1170.17	16.6	58.1	7.2	1.4	3.92
Sendafa	1971–1995	9.15	39.02	2560	1147.26	–	–	–	–	–
Bishoftu	1971–2000 1980–2004[1)]	8.73	38.95	1900	799.63	18.7	46.6	7.9	2.6	4.30
Mojo	1987–2006	8.62	39.12	1870	926.32	20.2	–	–		–
Mean	–	–	–	–	**1055.70**	**17.03**	**57.25**	**7.25**	**1.45**	**3.82**

[1)] Record length for relative humidity, sunshine hours and wind speed taken at that specific stations.
[2)] Record length for daily maximum and minimum temperature.
Explanation: *ETo* = reference evapotranspiration.
Source: own elaboration based on data of NMA [2007]

Table 4. Total estimated average annual flow of the sub-basins

Gauge station	Period	Latitude (°)	Longitude (°)	Elevation (m a.s.l.)	Catchment area (km^2)	Mean annual flow (mln m^3)
Holota[1)]	1975–2010	9.08	38.52	–	126.90	49.3
Berga[1)]	1975–2010	9.03	38.38	–	340.22	92.64
Teji[1)]	1975–2010	8.82	38.35	–	679.89	103.78
Awash Belo	1971–2010	8.85	38.4	–	2605.89	312.66
Melka Kunture	1971–2010	9.70	38.62	2014	4520.57	882.32
Akaki[1)]	1981–2010	8.87	38.78	2070	920.92	424.3
Melka Hombole	1971–2010	8.38	38.75	1850	7697.31	1341.44

cont. Tab. 4

Gauge station	Period	Latitude (°)	Longitude (°)	Elevation (m a.s.l.)	Catchment area (km^2)	Mean annual flow (mln m^3)
Mojo[1)]	1971–2010	8.60	39.10	1780	1458.63	563.12
Ungauged[2)]	–	–	–	–	2597.66	–
Total					**11753.6**	**1904.56**

[1)] Gauges at major tributaries and the rest indicates gauges along the main river.
[2)] Area above Koka Dam and below Mojo and Melka Hombole outlet.
Source: own elaboration based on data from NMA [2007].

DATA COLLECTION AND ANALYSIS

Data required for this study were collected from different sources. Daily stream flow, soil types (Tab. 1) and land use/cover data (Tab. 2) were obtained from Ministry of Water and Energy, Ethiopia. Daily meteorological data (Tab. 3) were obtained from the Ethiopian National Meteorological Agency (NMA) at eight different stations selected based on data availability and location with respect to the study area. Predictor data files were downloaded from Canadian Institute for Climate Studies website (http://www.cics.uvic.ca/scenarios/sdsm/select.cgi) and elevation grid data (resolution of 30 m) was obtained from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (https:/www.asterweb.jpl.nasa.gov/).

Collected meteorological data were pre-processed for missing, discontinuity and consistency. Missing data were filled using normal ratio method; closest station method and simple arithmetic mean whichever appropriately gave the best estimate [Youlong *et al.* 1999]. Double mass curve analysis for rainfall was used to check for any inconsistency. Further, homogeneity of stream flow time series was tested using rainbow software [Raes *et al.* 2006], which utilises methods of Buishand [1982] that is based on the cumulative deviations from the mean. After the available data were processed, filled and corrected for any inconsistency, the trend and correlation analysis for temperature and rainfall time series has been done. The procedure helped to identify and select appropriate climatic stations which were used for downscaling and thereby impact assessment. Accordingly, two stations (Addis Ababa and Ginchi) from the sub-humid part of the sub-basin and one station (Bishoftu) from the sub-arid part were selected for downscaling purpose.

DEVELOPMENT OF CLIMATE CHANGE SCENARIOS

Downscaling model calibration

The climate change scenarios produced during the study were from the outputs of the coarse resolution HadCM3 (Hadley Centre Coupled Model, version 3) general circulation model (GCM) which was downscaled to local scale for A2 (medium-high) and B2 (medium-low) emission scenarios. This GCM model was selected since it has wide application in many climate change impact studies, and provides large scale daily predictor variables used for downscaling purpose [Wilby, Dawson 2007]. Climate scenarios were developed only for rainfall, maximum and minimum temperatures since these parameters are the prime indicators of climate change. The rest of the climate variables were assumed constant for this particular study.

Statistical downscaling software (SDSM version 4.2) was used to downscale climate information from coarse resolution HadCM3 GCM to local/station level after proper calibration and validation. Calibration and validation has been done for selected station's predictand variables (Tab. 5) and daily observed predictor data. This predictor data were derived from the NCEP (National Center for Environmental Prediction) re-analysis that was downloaded from CICS for grid boxes representing the study area (i.e., BOX_11X_31Y for Addis Ababa and Ginchi stations and BOX_11X_32Y for Bishoftu station). The SDSM model uses linear regression techniques between predictor (i.e., large scale atmospheric variables like mean sea level pressure) and predictands (i.e., surface variables like temperature and precipitation) to produce multiple ensembles of synthetic daily weather sequences. This model was selected for its less need of knowledge about prevailing atmospheric circulation (i.e., its physics and chemistry), wider application in many regions of the world over a range of different climatic condition, easiness to run on personal computer, permitting uncertainty analyses through generated ensembles and requiring small computing time [Wilby, Dawson 2007].

Table 5. Observed meteorological data periods used during calibration and validation of SDSM

Station	Addis Ababa		Ginchi		Bishoftu	
	rainfall	T_{max}, T_{min}	rainfall	T_{max}, T_{min}	rainfall	T_{max}, T_{min}
Calibration	1971–1985		1971–1985	1981–1990	1971–1985	
Validation	1986–1995		1986–2010	1991–2010	1986–2010	

Explanations: T_{max} = maximum temperature, T_{min} = minimum temperature.
Source: own elaboration based on data from NMA [2007].

Climate scenarios generation

The regression weights produced during the calibration process of SDSM were applied to the time series outputs of the GCM for A2a and B2a emission scenarios to generate twenty ensembles of synthetic daily time series data for a period of 139 years (1961 to 2099). The final product of the SDSM was then found by averaging the twenty independent stochastic GCM ensembles summarised to monthly, season and annual time scales for inter-comparisons and was used as input for impact studies. This was done after dividing the future time series into three periods of 30 years: 2020s (2011–2040), 2050s (2041–2070) and 2080s (2071–2099).

HYDROLOGIC MODELLING USING HBV MODEL

The conceptual semi-distributed HBV model computes runoff from observed daily rainfall, daily temperature (if there is snow in the catchment), and estimates of long-term average monthly potential evapotranspiration. It also needs catchment characteristics of the study area and runoff data for calibration and verification. Detail of the model operation and its structure is available in other reports [Bergström 1992; IHMS 2006].

Catchment data

Due to its semi-distributed nature, HBV model needs subdivision of the basin into different elevation. Each elevation zone is also divided into different vegetation cover (forested and non-forested areas) [IHMS 2006]. The digital elevation model (DEM) of the sub-basin obtained from ASTER (https://asterweb.jpl.nasa.gov/) was processed using ArcSWAT in GIS interface to extract drainage area, drainage network and divide the area into different sub-catchments (Fig. 4) and elevation zones (Fig. 5). Further, each elevation zone was overlaid with the land cover/use of the study area to determine areal extent of different cover types (forest, field/cultivation, water bodies). Thus, the upper Awash River sub-basin is divided in to three sub-catchments: Hombole catchment (7697.6 km^2), Mojo River catchment (1458.63 km^2) and the area between Koka Dam and the other two catchments (2597.66 km^2) (Figs. 4, 5). For this particular study, the two gauged catchments (Hombole and Mojo) were used for further analysis since these catchments contribute more than 90% of the water resource of the basin and covers about 80% of the total area (Tab. 3).

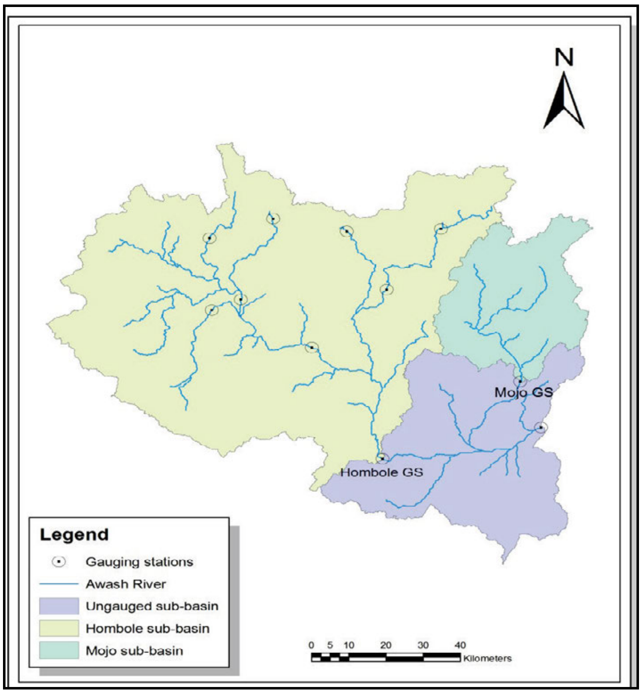


Fig. 4. Upper Awash River sub-basin divided in to three catchments; source: own study

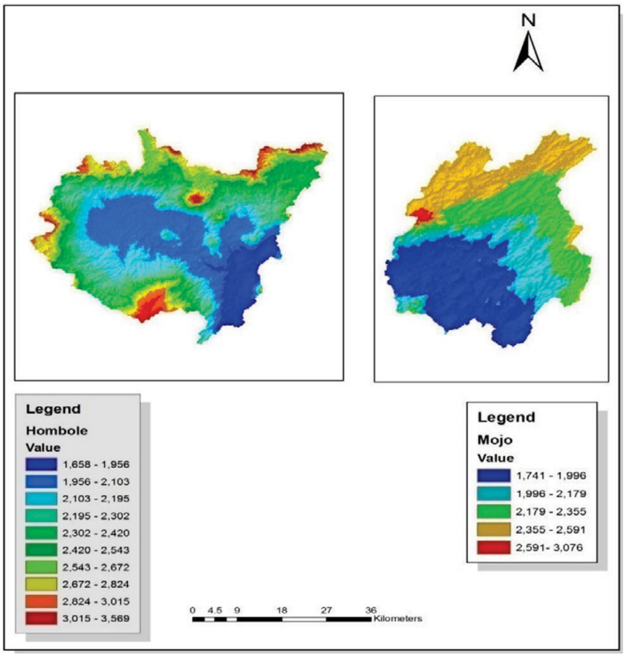


Fig. 5. Elevations divisions of Hombole and Mojo sub-basins; source: own study

Potential evapotranspiration

Long-term average monthly potential evapotranspiration was calculated using CROPWAT model; using historic average monthly values of temperature (T_{max}, T_{min}), wind speed, solar hours and relative humidity. But, only the downscaled future temperatures (T_{max}, T_{min}) were used for future potential evapotranspiration determination. The other parameters are estimated by the model itself once altitude, latitude and temperature values for intended station are given to it (details are available in Allen *et al.* [1998]). However, to keep consistency with the one calculated with full data as input, an adjustment was made by using the weight developed from potential evaporation calculated with full and limited data during base period. Accordingly, average monthly potential evapotranspiration were calculated for four stations: Addis Ababa, Ginchi, Bishoftu and Holota. The average future monthly potential evapotranspiration were calculated for Addis Ababa, Ginchi, and Bishoftu stations. These values were weighted using Thiessen polygon method and used as input to HBV hydrologic model during calibration and future stream flow simulation.

Areal rainfall and runoff

HBV hydrologic model requires daily rainfall as input. The collected rainfall data that represent the upper Awash River sub-basin were processed. Areal rainfall for each sub-basin considered for further analysis was computed by multiplying the point rainfall of each station with the weight computed by Thiessen polygon method in ArcGIS (Eq. 1).

$$\bar{P} = \frac{1}{A}\sum_{s=1}^{s=n}(A_s\ P_s) \qquad (1)$$

where: $\bar{P}$ = areal average rainfall, A = total area of sub-basin, A_s = area represented by the station, P_s = rainfall measured at station.

Similarly, for future runoff generation, the areal rainfall computed from adjusted downscaled rainfall at three stations (Addis Ababa, Ginchi and Bishoftu) were used. Adjustments were made by adding monthly temperature changes (deltas) to baseline period temperature values and by adding the monthly precipitation change factors (precipitation multipliers) to baseline rainfall (Eq. 2, 3) [HAILEMARIAM 1999; XU 1999; ZERAY 2006]. The remaining climatic parameters, land use and soil hydrologic parameters that were used in the model development during calibration and validation were assumed constant and remain valid under future conditions too [ZERAY 2006]. Daily river discharge data of the sub-basin at different sites obtained from Ministry of Water and Energy were used for the calibration and validation of the HBV model.

$$R_{\text{day, adj}} = R_{\text{day}}\left(1 + \frac{\%R}{100}\right) \tag{2}$$

$$T_{\text{day, adj}} = T_{\text{base}} + \Delta T_m \tag{3}$$

where: $R_{\text{day,adj}}$ = the rainfall (mm) on a given day at given station, $\%R$ = the percentage change in rainfall, $T_{\text{day,adj}}$ = the daily temperature (°C), ΔT_m = the change in temperature (°C).

CALIBRATION AND VALIDATION OF HBV MODEL

The HBV model calibration and validation has been done using trial and error procedure specified in the SMHI manual following a certain order [IHMS 2006]. The considered model parameters are: (i) volume parameters, (ii) soil parameters, (iii) response parameters and (iv) damping parameters. Since snow is not experienced in Ethiopia in general and the catchment in particular, snow parameters were not used for this study. After calibration, the model was validated against independent data withheld from calibration. Finally, the model performance was evaluated in three different ways: (1) visually inspecting and comparing the calculated and the observed hydrograph, (2) calculating the Nash–Sutcliffe efficiency (E_{NS}) criteria (Eq. 4) acc. to NASH and SUTCLIFFE [1970], and (Eq. 3) calculating the relative volume error (RVE) (Eq. 5) [IHMS 2006].

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{\text{sim}(i)} - Q_{\text{obs}(i)}\right)}{\sum_{i=1}^{n}\left(Q_{\text{obs}(i)} - \bar{Q}_{\text{obs}}\right)^2} \tag{4}$$

$$RVE = \frac{\sum_{i=1}^{n} Q_{\text{sim}(i)} - \sum_{i=1}^{n} Q_{\text{obs}(i)}}{\sum_{i=1}^{n} Q_{\text{obs}(i)}} 100\% \tag{5}$$

where: $Q_{\text{sim}(i)}$ = simulated flow, $Q_{\text{obs}(i)}$ = observed flow, = average of observed flow.

E_{NS} can have values ranging from −∞ to 1. If the simulation is perfect, E_{NS} is equal to one. An efficiency of E_{NS} is equal to zero indicates that the model predictions are as accurate as the average of the observed data. If the accuracy of the simulation result is smaller than the average value of the measured variables, then E_{NS} will have a negative value.

ANALYSIS OF CLIMATE CHANGE IMPACTS ON STREAM FLOW

Climate scenarios developed by downscaling at representative stations (Addis Ababa, Bishoftu and Ginchi) were used to simulate future runoff. The climate model outputs (precipitation and temperature) from HadCM3 were used as an input to HBV hydrologic model to simulate the daily stream flow. Then, the simulated stream flows were accumulated and analysed on monthly, seasonal and annual bases for the three time horizons projected in the future (2020s, 2050s and 2080s), and compared to the historic data of the base period.

RESULTS AND DISCUSSION

CALIBRATION AND VALIDATION OF SDSM MODEL

The explained variance (R^2) and standard error (SE) values obtained during calibration and validation of SDSM model are indicated in Table 6. The results found showed that simulated maximum temperature has better agreement with the observed time series than the other two variables. The simulation of rainfall though showed a relatively lesser agreement as compared to the maximum temperature; the result is quite acceptable due to the fact that precipitation is a conditional process [WILBY, DAWSON 2007]. This study results are acceptable compared to some similar downscaling results of other studies [HARPHAM, WILBY 2005; MULUGETA 2009; ZERAY 2006].

Table 6. Calibration and validation of rainfall and temperature at different station

Station	Parameter	Explained variance (R^2)		Standard error (SE)	
		calibration	validation	calibration	validation
Addis Ababa	rainfall	0.151	0.132	0.436	0.440
	$T_{\max}$	0.572	0.547	1.608	1.608
	$T_{\min}$	0.488	0.418	1.720	1.760
Ginchi	rainfall	0.111	0.104	0.410	0.430
	$T_{\max}$	0.504	0.443	1.626	1.823
	$T_{\min}$	0.287	0.238	2.162	2.180
Bishoftu	rainfall	0.138	0.104	0.415	0.435
	$T_{\max}$	0.415	0.406	1.639	1.642
	$T_{\min}$	0.414	0.312	1.745	1.865

Explanations: $T_{\max}$ = maximum temperature, $T_{\min}$ = minimum temperature. Source: own study.

Some comparison statistics and climatic patterns for average monthly rainfall totals and maximum and minimum temperatures for selected stations are also presented in Table 7 and Figures 6–8 so as to see the skill of the model in reproducing the historic parameters. As can be observed in Table 7, the SDSM is able to reproduce the historical values except the extreme events. The model underestimates the farthest values in upper extremes and keeps more or less the average events. In addition, the model is also able to detect lower extreme events. The lack of replicating the extreme conditions was also reported by one of the model developers [WILBY *et al.* 2004] and other independent studies [CHU *et al.* 2010; YANG *et al.* 2012; ZERAY 2006]. The model is capable of fairly replicating the average historic monthly/seasonal/annual climatic patterns (Figs. 6–8).

Table 7. Comparison of observed and generated monthly total rainfall, mean maximum and minimum temperature values of the base period at Addis Ababa station

Statistics	Max	Min	Mean	*SD*
Monthly total rainfall (mm)				
Observed	317.9	0	86.0	86.4
Average of 20 ensembles (A2a)	253.8	0.8	73.9	66.7
Average of 20 ensembles (B2a)	243.5	1.1	73.8	65.9
Mean monthly maximum temperature (°C)				
Observed	27.2	19.5	23.0	1.5
Average of 20 ensembles (A2a)	24.9	20.2	22.7	1.3
Average of 20 ensembles (B2a)	24.9	20.1	22.7	1.3
Mean monthly minimum temperature (°C)				
Observed	12.1	3.1	8.9	3.1
Average of 20 ensembles (A2a)	11.1	2.4	8.6	2.1
Average of 20 ensembles (B2a)	11.1	2.1	8.6	2.1

Explanations: *SD* = standard deviation, A2a, B2a = climate scenarios.
Source: own study.

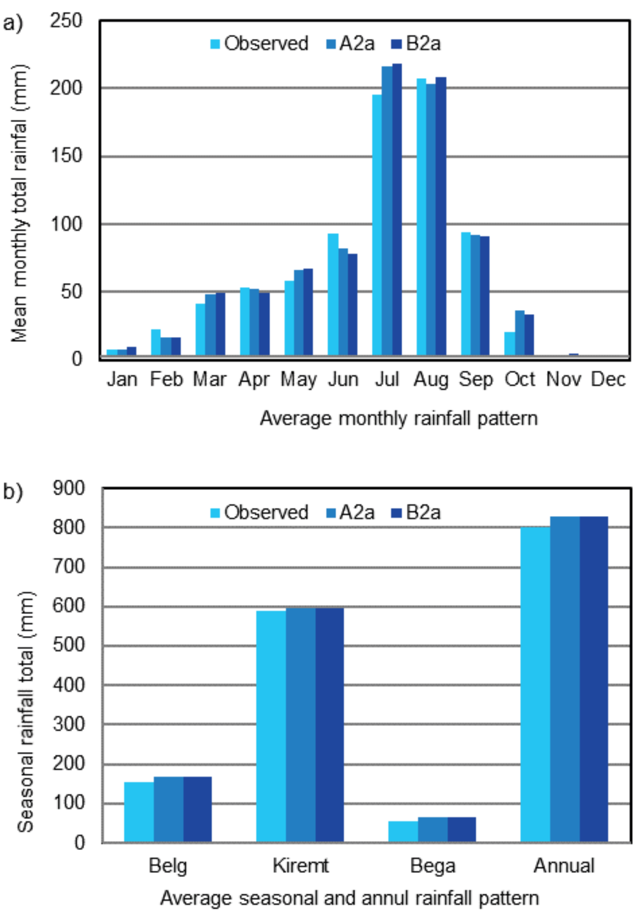


Fig. 6. Average monthly (a) and seasonal (b) rainfall at Bishoftu station for the base period; A2a, B2a = climate scenarios; source: own study

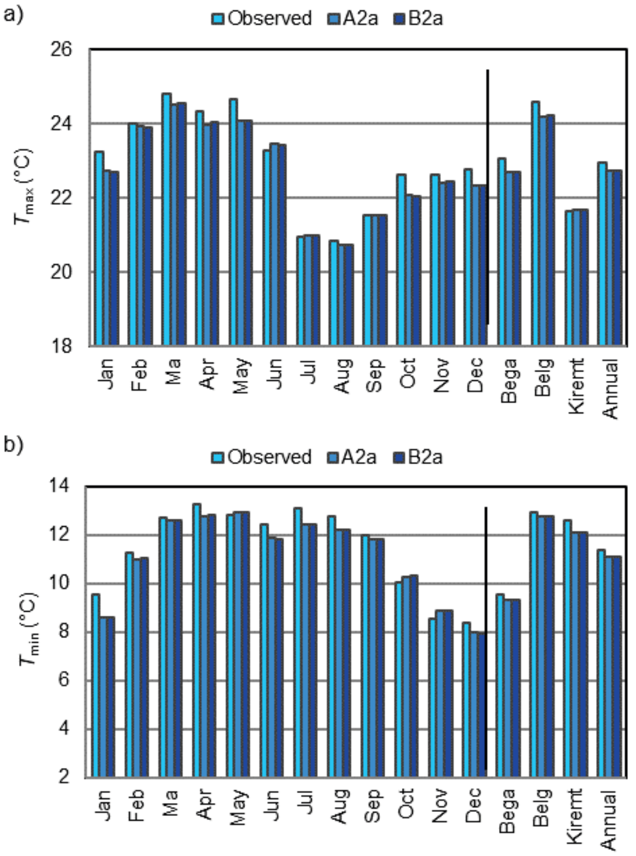


Fig. 7. Average monthly and seasonal: a) maximum and b) minimum temperatures pattern at Bishoftu station for the base period; A2a, B2a = climate scenarios; source: own study

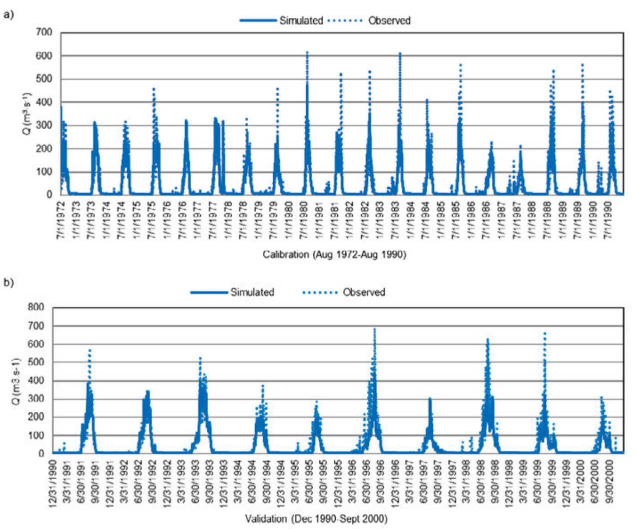


Fig. 8. Simulated and observed runoff for Hombole catchment during: a) calibration, b) validation; source: own study

IMPACT OF PROJECTED CLIMATE CHANGE ON WATER RESOURCE AVAILABILITY

The results of hydrologic model calibration and validation for the two stations are presented in Tables 8–9. Table 8 presents the model parameter values and Table 9 presents the values of performance parameters during calibration and validation. As indicated, HBV model performs well during the calibration period ($0.62 < E_{NS} < 0.81$) when compared to the validation

Table 8. Optimum parameters values used during calibration of HBV model

Catchment	Parameter									
	Rfcf	*FC*	Lp	Beta	*Cflux*	*Khq*	Alfa	Perc	*K4*	Maxbaz
Hombole	0.654	460	0.6	1.0	0.7	0.09	0.95	0.25	0.002	1
Mojo	1.050	350	0.8	1.5	0.1	0.20	1.10	0.15	0.001	0.35

Explanations: *Rfcf* = rainfall correction factor, *FC* = maximum soil moisture storage (mm), *LP* = limit for potential evapotranspiration, Beta = an exponent in formula for drainage in soil, *Cflux* = capillary flow from the upper response box to the zone of soil water, *Khq* = the recession coefficient for the upper response box, Alfa = a parameter used to fit the higher peaks in to the hydrograph, Perc = percolation from the upper response box to lower response box, *K4* = a recession coefficient for the lower response box, Maxbaz = number of days in the transformation routine of the hydrograph.
Source: own study.

Table 9. Values of objective functions obtained during calibration and validation of HBV model

Catchment	Calibration		Validation	
	E_{NS}	*RVE* (%)	E_{NS}	*RVE* (%)
Hombole	0.81	0.024	0.77	13.80
Mojo	0.62	8.59	0.57	−0.58

Explanations: E_{NS} = Nash–Sutcliffe efficiency, *RVE* = relative volume error.
Source: own study.

period. The obtained values are also in the recommended range [DECKERS 2006] that is well over 0.6 for hydrological model to be used for further analysis. The *RVE* again is found to be in the range of ±10% except during validation period of Hombole catchment which is taken as satisfactory [GETAHUN, VAN LANEN 2015; WALE 2008].

The plots of daily observed and simulated flow during both calibration and validation periods were illustrated in Figures 8 and 9 for both catchments. Visual inspection of the observed and simulated hydrographs for Hombole catchment showed that the performance of the model in simulating the base flow, rising and recession limb of the hydrographs was found good, but it under-estimates near peak and peak values. However, the overall flow trend was well simulated by the model (Fig. 8). In contrast to Hombole catchment the model fails to reasonably capture the flow characteristics of Mojo catchment (Fig. 9). This might be due to flow characteristics of the catchment (i.e. quick response), functional structure of the model itself [SEIBERT 1997] which is usually good for monomodal rainfall conditions and slow responding catchment or may be due to quality of the data.

After iterative model runs, optimum parameter sets that produced the best possible agreement between observed and simulated discharges for Hombole and Mojo catchments were selected (Tabs. 8, 9). These parameters were then used by the HBV model for runoff simulation during current and future time periods. Although the model performance parameters for Mojo catchment were found to be reasonably good to be used for further analysis (Tab. 9), this catchment is not considered for further impact studies due to the above mentioned reasons. Furthermore, the impact on the ungauged part of the sub-basin is not dealt with although it is possible to transfer/develop the model parameters for ungauged catchment through different methods (regionalisation, area ratio, spatial proximity, use of default parameter values). This is because the runoff generated by

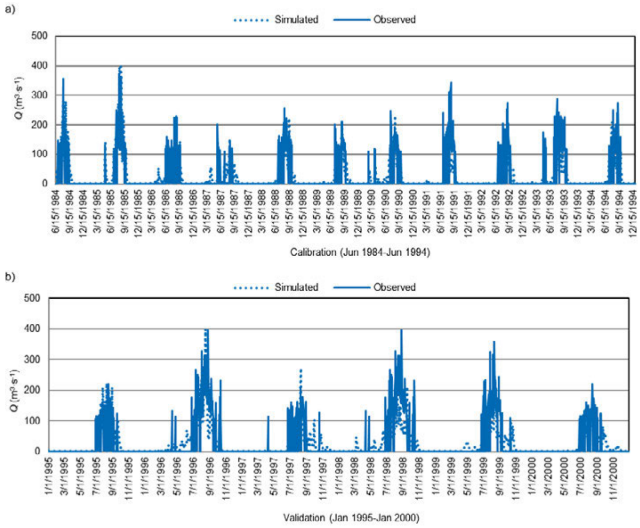


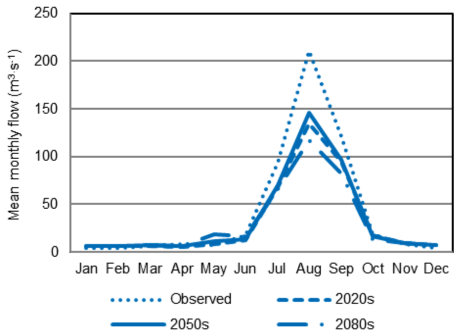
Fig. 9. Simulated and observed runoff for Mojo catchment during: a) calibration, b) validation; source: own study

different hydrologic models specially lumped conceptual ones by using parameters from these methods is not reliable particularly for impact studies [DZUBAKOVA 2010]. Therefore, for impact assessment of climate change on water resources of the sub-basin, water resources up to Hombole catchment outlet was used for this particular study.

The projected daily runoff using the calibrated HBV hydrologic model was summarised to monthly/seasonal time scales and analysed relative to base period. Figure 10 shows the average monthly flow distributions of the observed and projected future flow values at three bench mark periods. It is observed that there are decreasing trend from June to October including April; and increasing trend from January to March and November to December under both emission scenarios. The magnitude of change (decrease) in mean monthly flow for rainy months ranges from 6.7% (under B2a at 2020s) in September to 44.3% (under A2a at 2080s) in August (Tab. 10).

Seasonally, there is an apparent increase in mean flow relative to the base period in Bega[1)] at all the three periods under both emission scenarios (i.e. by over 50%). Belg[2)] flow will be expected to decrease by up to10.8% (under B2a) at 2020s and it

[1] Bega represents dry (winter) season during the months of October to February.
[2] Belg represents small rainy season during the months of March to May.



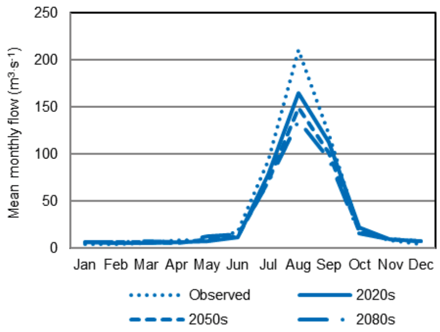


Fig. 10. Average monthly flow distributions of the observed and projected flow values at three bench mark periods under A2a and B2a emission scenarios: a) observed and projected discharge with downscaled data under A2a, b) observed and projected discharge with downscaled data under B2a; source: own study

Table 10. Percentage change of runoff of rainy months relative to baseline period

Months	Scenario					
	A2a			B2a		
	2020s	2050s	2080s	2020s	2050s	2080s
June	−29.7	−24.9	−8.3	−34.7	−30.9	−16.7
July	−27.6	−24.7	−29.8	−16.1	−23.5	−24.6
August	−36.2	−30.7	−44.3	−22.0	−29.2	−35.7
September	−21.8	−19.9	−32.0	−6.7	−16.2	−21.9

Explanations: A2a, B2a = climate scenarios.
Source: own study.

will be expected to increase by about 47.6% (under A2a) at 2080s. But significant general decreasing trend during Kiremt[3] season under both emission scenarios are expected. Kiremt flow will decrease in the range of 17.1% (under B2a at 2020s) and 36.4% (under A2a at 2080s). The observed decreasing trends of flow during Kiremt season and that of rainy months are attributed to increasing trend of potential evaporation during these season/months and relative decreasing trend of rainfall at Ginchi station that weighs out the increasing trend in rainfall at Addis Ababa and Bishoftu stations. This is consistent with that increase in potential evaporation and decreases in rainfall are expected to reduce the mean flow from a given watershed (Tab. 11).

Table 11. Seasonal and annual percentage change of runoff relative to baseline period

Season	Scenario					
	A2a			B2a		
	2020s	2050s	2080s	2020s	2050s	2080s
Bega	+20.8	+17.4	+9.0	+32.8	+20.5	+14.0
Belg	−5.4	+14.2	+47.6	−10.8	+0.2	+21.2
Kiremt	−30.2	−26.3	−36.4	−17.1	−24.5	−28.8
Annual	−25.2	−21.2	−29.4	−13.0	−20.0	−23.4

Explanations: A2a, B2a = climate scenarios. Source: own study.

[3] Kiremt represents main rainy (summer) season during the months of June to September.

Significant overall decreasing trend in mean annual flow is also observed in the sub-basin. It might be expected that mean annual flow will decrease in the range of 13% at 2020s under B2a emission scenario to 29.4% at 2080s in the case of A2a emission scenario (Tab. 11).

The result of this study is in agreement with other studies in Awash River Basin [Hailemariam 1999; Daba *et al.* 2016; Zeray 2006] and also for upper Blue Nile Basin [Kim *et al.* 2008]. Zeray [2006] studied the impact of climate change on water resources within Ziway catchment and found similar decreasing trend of flow volume of rainy months (June–September) and decreasing trend in Kiremt flow volume varying between 11.8 and 28.4% for the A2a scenario and between 16.5 and 27.8% for the B2a scenario. He also found that a significant reduction in total average annual flow up to 19.47% under A2a and by up to 27.43% under B2a scenarios. Hailemariam [1999] reported that runoff will decrease in the range of 10 to 34% using climate scenarios generated from large scale GCM (i.e. by CO_2 doubling and transient scenario) over Awash River Basin. Daba *et al.* [2016] found a reduced stream flow of upper Awash River Basin by 2.46% (2050s) to 18.14 (2080s) under A1B emission scenario. Kim *et al.* [2008] also got flow reduction by about 11% under HadCM3A2a at 2050s for upper Blue Nile Basin.

CONCLUSIONS

The impact of climate change on water resources availability of upper Awash River sub-basin had been studied to address such likely problems. The future climate change scenarios were generated by using SDSM and output of GCM (HadCM3). HBV hydrologic model was used to simulate future daily stream flow under changed climate. This simulated runoff was accumulated to monthly, seasonal and annual time scale and analysed relative to baseline period (1971–2010) so as to evaluate the impacts on water resources availability of the sub-basin due to likely changes.

The study confirmed that the SDSM is able to simulate all except the extreme climatic events. The model underestimates the farthest values especially the upper extremes and keeps more or less an average event. Nevertheless, the simulated climatic variables generally follow the same trend as the observed one. The model simulated maximum temperature more accurately than minimum temperature and precipitation. The less performance of precipitation simulation is attributed to its nature of being conditional process. It also more accurately captured monthly and seasonal climatic variables averaged over years than individual daily values.

Simulation of flow by HBV hydrologic model revealed that there are significant mean flow reductions in the future during Kiremt and apparent increase during Bega seasons, respectively. Belg flow volume on one hand shows a decreasing trend at 2020s and shows increasing trends at 2050s and 2080s on the other hand. A significant mean annual flow reduction is also expected in the future at all three periods under both emission scenarios. It will decrease between 13–29.4% compared to baseline period.

HBV hydrologic model has proved to simulate reasonably well the hydrological process of the Hombole watershed but failed to do so for Mojo catchment. The model is able to capture daily flow patterns of Hombole watershed where rainfall is unimodal in pattern. This was justified by obtained Nash–Suttcliffe simulation efficiency and *RVE* values during model calibration and validation. Hence, it is logical to conclude that the HBV model can accurately explain the hydrological characteristics of the watershed and hence can be used for future run off simulation and impact assessment.

Using GCM (HadCM3) and downscaling its output to station (point) level so as to reduce the uncertainties attached to it (coarse resolution). The results have shown that there is likelihood of a significant reduction of water resources of upper Awash River sub-basin. Therefore, policy makers, research and development support institutions should consider different adaptation options like efficient irrigation water management, water harvesting technologies (in-situ and off-situ), construction of reservoirs, water recycling, development of ground water sources, use of drought resistant crop varieties etc. to reduce the likely impact.

The study involved a series of models and model outputs, which are based on certain inherent assumptions. Therefore, a further independent study is required to verify and improve the result of this study. Other hydrologic models (such as physically based models like SWAT) or regional based models can also be tested for the watershed for climate and land use change impact studies. The future studies should also consider land use change, population growth, agriculture and industrial growth in parallel or in combination with climate change.

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